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ABSTRACT

A review is presented of the radiation energy transfer rates characteristic of the environments for advanced entry missions, and of the techniques suitable for simulating these heat transfer rates in the laboratory. At entry velocities greater than 45,000 ft/sec there is at least a factor of 2 or greater uncertainty in the estimated value of the radiative heat flux incident on the vehicle surface. In particular, there is a lack of quantitative experimental data on radiation emitted in the ultraviolet (<2000Å) portion of the spectrum. Little systematic information is available on the effect of the spectral distribution of incident radiation on material behavior. As a result, the question of whether a laboratory radiative reentry simulation facility must be designed to exactly duplicate the spectral distribution characteristic of the reentry environment is still open. The most promising techniques for laboratory simulation of advanced radiation environments appear to be those associated with the continuous arc discharge. Radiation fluxes which are characteristic of advanced manned reentry environments, can be obtained by direct exposure of material specimens to an arc column. Radiation lamps can produce heat fluxes of the order of 1 to 2 kw/cm^2. Outstanding problems pertain to the quantitative prediction of radiation environments, characteristic of flight speeds greater than 45,000 ft/sec, determination of the effect of different spectral radiation distributions on material behavior, determination of the effect of variations in the ratio of convective to radiative heat transfer on material behavior, and the design of efficient optical systems for high power (100 kw to 1 megawatt) radiation lamps.

INTRODUCTION

During the first several years of ground testing of heat shield materials and structures of IRBM and ICBM reentry vehicles, several types of radiant heating systems were utilized for simulation of the convection heating. In general, these systems (the compact arc, the carbon arc, and the solar furnace) were replaced with combustion jets, including several types of rockets, pebble-bed heaters, plasma-arc heaters, and the multi-mounted shock facilities. Now, however, planetary entry at superorbital velocities (lunar and planetary probes), or entry of exceptionally blunt probes (designed for maximum atmospheric breaking) have necessitated a re-evaluation of these radiation simulation facilities.

DEFINITION OF RADIATION SIMULATION REQUIREMENTS

A literature search to establish the radiant heating fluxes associated with general vehicle geometry and trajectories for superorbital velocities, particularly over 40,000 ft/sec, provided somewhat disappointing results. Predictions at the higher velocities differ by factors of more than two[1-11]. A generalization of this uncertainty for velocities up to 65,000 ft/sec is shown in figure 1. (Data used for this figure are from references 3-8,10,11.)

Assuming that the major irradiance of the vehicle is due to emission from the gas-stagnation region which is in local thermal equilibrium (i.e., neglecting non-equilibrium radiation effects) and is optically thin, then the radiant flux at the stagnation point may be estimated by equation (1).

$$\dot{q}_{rad} = 2 \pi \delta F J \qquad (1)$$

F is minor correction factor accounting for shock-wave curvature, δ is the shock standoff distance and J is the radiant intensity (power/volume-steradian) of the radiating gas. Estimates of δ (available in the literature[1-6]) are usually formulated in terms of flight parameters which include the effective vehicle nose radius. In general, these estimates of δ agree to within 30 percent. Suggested values of F are also in the literature[2,4], as are values of J.[3-6,12-14]

The primary experimental sources of data for estimating the radiant intensity J, are shock tubes and ballistic ranges[3-8,10,11]. To make a comparison of the data from these sources in terms of flight velocity and stagnation gas density, corrections were made to the data of references 4,5 using the gas-dynamic charts of reference 15. With these corrections, a data comparison is shown in figure 2 where the intensity has been density normalized by the relation

$$J/(\rho/\rho_o)^{1.7} \alpha \ f \ (V_\infty) \qquad (2)$$

which was inferred from references 3 and 10 for thermal equilibrium conditions. These data tentatively agree to within about a factor of two, however, when examining the data in figure 2 it must be borne in mind that the density normalization used is only approximate.

In addition to the shock tube and ballistic range data, figure 2 presents for comparison, semiempirical estimates of air radiation obtained from the diagnostics of arc heated, optically-thin,

plasma columns in local thermal equilibrium[13,14]. As shown in figure 2, the lower curve represents estimates of continuum radiation while the upper curve includes estimates of both atomic line and continnum radiation. As the shock tube and ballistic range data[3-8,10,11] excluded emission in the wavelength range below 1500Å, the above semiempirical estimates were prepared for a similar limited spectrum. As illustrated in figure 2, the radiation estimates from the arc-heated plasma column tend to envelope the experimental data. If one extends these estimates to include flight velocities below 30,000 ft/sec, molecular mechanisms should be included. For flight velocities greater than 60,000 ft/sec ionic line radiation should be included.

Estimates of radiant emission in the far UV region (λ<2000Å)[13,14,16-18] indicate that this emission is large compared to that emitted in the remaining spectrum. Some estimates based on a gas at 16,000°K indicate that the energy transfer by this means is greater than a factor of 5 to 10 times that by thermal conduction.[19] The actual radiation values for this region are far from being well determined. Measurements of the continuum for oxygen agree relatively well with theory, but there is a paucity of continuum data on nitrogen particularly in the regions where it is of the greatest significance. There are factors of variance of ten between measurements of line radiation of nitrogen in the UV compared with recent theory[19], however this is better than the case of UV line-radiation measurements for oxygen for which there are none. (It is expected that this lack of data will soon be corrected, as many investigators are giving

their attention to the problem.) One particularly promising technique is being developed by Morris in which an arc-heated gas, isolated by a helium or argon window, is viewed by a vacuum ultraviolet spectrometer[20]. In spite of this general lack of data for UV radiation, a calculation has been made for comparison purposes of the total line and continuum radiation of wavelengths less than and greater than 2000Å for nitrogen at one atmosphere (see figure 3).

In the calculation of these estimates, it was assumed that the gas was optically thin and no blackbody ceiling was placed on the line radiators. (The continuum radiation of wavelengths greater than 2000Å was based on experimental data from reference 13. A great significance of the far UV emission is its absorption or transmission. If the greater part of this radiation leaves the gas cap, use of the experimental data of references 3-8, 10,11 in equation (1) would only assess, at best, the irradiance to an order of magnitude. In addition, one would have to consider the change of shock-layer gas enthalpy by the radiant emission and the effect on convective heating[1]. However, if these emissions are predominantly self-absorbed, a re-evaluation should be made of the thermal conduction estimates which could greatly influence gas-cap enthalpy gradients[21].

Based on the foregoing arguments, any definition of radiation-simulation requirements will be only an order of magnitude. Recognizing this fact, radiation charts (see figures 4-7) have been

prepared which provide estimates of the total intensity for wavelengths $\lambda < 2000\text{Å}$. These charts were based on the seemingly valid semiempirical estimates of atomic line and continuum emission for wavelengths greater than 2000Å given by reference 13. For wavelengths less than 2000Å, the total continuum and atomic line emission was estimated using methods described in references 13 and 14. These estimates include only those flight velocities and/or gas temperatures where molecular and ionic radiators can be neglected and have assumed optically thin conditions. For comparison purposes, equation (1) and figures 5 and 6 have been used to estimate the irradiance of a vehicle having 1 foot effective nose radius, R. For these calculations a ratio of δ/R, equal to 0.045, was chosen. This value according to the reference 2 is applicable for flight velocities in the range of 20,000 to 60,000 ft/sec and altitudes of 100,000 to 240,000 ft. From reference 4 the value 0.84 was used for the correction factor F. The results of these calculations are shown in figure 8. (The calculation of the flight velocity for figures 2, 7, and 8 was based on the energy conservation law for normal shock solutions

$$\begin{aligned} V &\simeq \sqrt{2h_s} \\ h_s &\gg h_\infty \end{aligned} \qquad (3)$$

where the diminishing of enthalpy due to radiant emission was not considered.)

RELATIONSHIP OF FLIGHT PARAMETERS TO SIMULATION REQUIREMENTS

The spectral radiance of a gas significantly varies with composition, pressure, and temperature. Therefore, the spectral distribution of radiant energy from the gas cap, as seen by the heat-shield material, represents a rather complicated phenomenon. There are not only pressure, temperature, species, and composition variations and gradients, but also gas phase and surface combustion, radiation absorption, blocking and reradiation[1]. Production of all of these parameters can only be accomplished in a flight test. However, experience has shown in other aspects of laboratory simulation that meaningful evaluations and engineering design data can be obtained from less than exact duplication of flight conditions. What now remains is the establishment of relative importance of the several factors mentioned, necessary model sizes, combined radiative and convective heating, and the effects on all of the factors resulting from parameter changes associated with the entry trajectory. As there are only several facilities capable of obtaining useful data in this field, there is very little actual data on which to base decisions. The more significant reports are those of Howe and Viegas[1], Diaconis et al[22], Lundell et al[23], Howe[24], Lundell et al[25], Louis et al[26].

In spite of the availability of these several references, data in this field are sparse and inconclusive. One is not able at this time to specify which parameters in radiant heating simulation of entry conditions must be duplicated.

From data on the more simple heat-protection materials such as teflon, graphite, and phenolic nylon, it would appear that if the total net heat to the material surface occurs with a constant surface temperature, then the material performance is nearly constant regardless of the ratio of convective to radiative heating. This is confirmed in the data of Lundell et al[25]. It should be noted that considerable significance can be attached to duplication of the total net heating input and the maintainance of a surface temperature equivalent to that which would be associated with flight conditions. Constant gross heating with variations of the ratio of convective and radiative heating seem to produce significant changes in total net heating.

Source uniformity is another interesting parameter that appears to be greatly influenced by the material to be tested. Several investigators have noted that a source that is quite nonuniform, exhibiting a particular high brightness in the center, can be used to test materials that are char-forming without causing any apparent nonuniform heating. However, it has also been noted that such a source will directly reflect the source nonuniformities on materials such as teflon. Therefore, source uniformity must also be assessed according to the types of materials to be evaluated.

The importance of the length of a test has been a difficult parameter to assess even for straight convective heating. In convective heating this parameter is strongly dependent on the type of material being tested and the particular application of interest. General testing experience has shown that if a material was being

subjected to convective heating fluxes of less than 100 BTU/ft^2 sec, it requires about 10 minutes of test time for the material to arrive at a steady state. For fluxes of about 200 BTU/ft^2 sec, it takes on the order of 2 minutes. For fluxes greater than 500 BTU/ft^2sec, it takes about 30 seconds or less. It is cautioned that these estimates may be only applied in general, and that they might not apply at all to a given particular type of material. For pure radiative or for a combined radiative and convective heating test, the general test time applicable for convective heating might have to be doubled or even quadrupled, due to the factors of surface reflectance or boundary layer blocking. It should be noted that in many ballistic vehicle applications, the heat-shield material does not reach a steady-state condition during the reentry. Under conditions such as this, one may not need to test until a steady-state condition is achieved. It therefore appears necessary that both the application and the particular material must be examined, and perhaps, some preliminary material tests will be required to establish this parameter.

Importance of a matched spectral distribution in a radiation simulator cannot be determined at the present time. Data in this area are extremely sketchy, and in one instance even contradictory. At low net flux levels, less than a few watts/cm^2, it has been observed that certain organic materials may react differently chemically. A good example of this is the film coatings which produce different colors dependent on the spectral distribution of the incident

radiation. It is also a well established fact that a material's emissivity is wavelength dependent. Though slight, this has some effect on reradiation and hence the net heat flux. In several cases similar heat-shield type materials have evidenced similar performance when tested with either a pure radiative heating flux, an argon arc lamp or a pure convective heating flux, from a typical arc plasma heater.

RADIATION SOURCE EVALUATION

The radiation heating source consists primarily of the radiant energy source and, in some instances, an optical system for the concentration, focusing, and modulation of the radiant energy. In the absence of well-defined guide lines for parameters to be simulated, a general evaluation has been made of potential sources based on the following general requirements: 1) Radiant flux attainable, 2) spatial and temporal uniformity of flux at test section, 3) combatibility with convective heating sources, 4) spectral distribution, 5) operational characteristics, and 6) economics. Table 1 presents a summary review of the state-of-art potential sources in terms of these parameters. (Some types of available sources have not been listed; however, it is felt that those listed are represented.)

A single radiation source that will have all of the desired capabilities or characteristics is not available at the present time, nor is it likely that one will develop in spite of many possible advances. To simulate an entry condition for a vehicle being exposed to a stagnation temperature of 12,000 ^{o}K in air, one might desire a source that could produce a radiant flux of 1-2KW/cm over a 10cm^{2} area and have a spectral

distribution which would approximate a black body of 12,000°K. The solar furnace can produce the desired flux level having a spectral distribution match of 6000°K but the source has a rather poor uniformity over a limited target area. A filtered-carbon arc source can provide a fairly well matched spectral distribution, but the flux levels for this target size are quite limited. The state-of-the-art of high pressure compact arcs is undergoing a very rapid change. These units offer a great deal of flexibility, particularly for large size models and low flux levels; however, these sources, by their very nature, are flux-level limited. The remaining type of source of interest is the plasma arc source. (The significant difference between the high pressure compact arc with collant-cooled electrodes and the so called plasma arc generator, is the circulation and/or flow of the radiating medium or gas. There is also some difference in input power levels; 20kw high pressure compact arcs are nearing operational status, whereas megawatt plasma generator lamps are within the state-of-the-art.) The plasma arc generator sources offer the features of being able to operate at high power levels at high pressures with a variety of radiating mediums. For the particular problem indicated, this type of source can provide the flux level desired uniformly over the target area, but would likely not have the 12,000°K black-body distribution. Following is a general review of the plasma generator type sources. References 12 and 27 provide additional detail concerning the other radiation sources, associated optics, and spectral distribution of the flux.

PLASMA-ARC GENERATOR SOURCES

A concentrated effort has recently been applied to the study of the plasma arc heater as a possible radiant energy source.[28-30] The plasma

arc heater is able to maintain an arc discharge with maximum temperature in excess of 20,000°K on a continuous time basis. The continous radiation from such an arc column may be a few watts/cm to several tens of kilowatts/cm depending on the arc current, voltage gradient, pressure level, and type of working fluid. This type of source has been utilized to provide both radiant and convective heating for material specimens placed in the vicinity of the arc column.[22] This type of device is also being developed exclusively as a radiating source.[28, 29, 30] When the source, used solely as a radiation source, one or the other of two techniques are being used; 1) models are placed in the proximity of the arc column to be irradiated by it (see figure 9). (This method differs from the technique sited above from reference 22 and described in a following section, in that the arc-heated gas flow or radiating media in this source is injected and constrained in a manner such that it does not come in contact with the model being tested.) 2) Associated with the radiating arc column, are collecting and/or concentrating systems so that the model being tested is not enclosed within the geometry of the radiation system.(see figure 10). The first of these two techniques offers the advantage of moderate to high flux levels at a moderate cost,but has the inherent problems of model-size limitation, source nonuniformity and calibration uncertainties. These characteristics pertain also to the combined convective and radiative heating source cited above. The second technique may be somewhat more complex and entails greater costs in that associated optics are required and should be designed as an intergal part of the radiating source (either external or internal of the arc housing). This type of source, however, offers the potential of greater flexibility of model size, shape, environment (pressure, gas

composition) and placement. Depending on the system design, multiple units may even be used, and greater and more uniform flux levels may be obtained. A multiple mounting of this type of source is shown in figure 11.

Experimental results with a particular plasma arc generator,[28] have shown that the radiation emited by the arc column increased with increase in arc current (resulting in higher column temperatures if other factors are kept constant) and pressure level, but decreased with increase in mass flux rates, mean voltage gradient, and external magnetic field. These results were obtained utilizing an argon arc column of 100 to 2000 amperes and pressure levels of 1 to 10 atmospheres. (Some preliminary results also indicate that in spite of the increase in radiation observed with higher pressure, optimum operation may occur at pressure levels between 15 and 35 atmospheres.)

The spectral distribution of plasma arc-generator radiation sources are dependent on the radiating media, characteristics of any optical elements (windows, reflectors, or concentrators) and arcing conditions (column temperature, pressure, etc.) In most instances, the selection of the radiating media is the main consideration regarding spectral distribution. For example, helium provides a much greater flux in the UV than does argon or zenon, whereas zenon is much stronger in the IR. Argon however, is a more optimum media for operation in the plasma-arc source as it has a higher total radiating efficiency over the usable spectral range (energy transmitted to the model per unit power input) and has fewer source operational problems. Regardless of the direct match of the spectral distribution between arc heated air (neglecting affects of cut-off or absorbtion of

portions of the radiation by optical elements or differences of pressure and temperature) and the actual vehicle-material environment, it is generally undersirable to operate the source with air or its constituents except in the direct radiating units. The reason for this is that air has a very low radiation delivered to the model per unit input power efficiency as compared to many other gases. It also causes more severe operational problems than the higher efficiency inert gases.

Filters, of course, can be used to improve the spectral match. The major disadvantages of their use are the subsequent drop in total flux and some reduction of intensity of desired bands resulting from the cut-off or reduction of undesired bands or wave lengths.

One possible method for improving the spectral match is by filling in spectral gaps by providing additives to the basic radiating (carrier) gas. Several investigators have reported that the spectral distribution of a source, particularly an arc source, can be greatly modified by the addition of powders to the stabilizing gas.[29,30] This may have an interesting potential, however it also has been observed that the additives may produce undersirable side effects such as damage to the generator source or optics, or lower conversion efficiencies. For example, use of additives with relatively low ionization potentials (e.g., the alkali metals) can be expected to increase infrared radiation (including the continuum).This would be done, however, at the expense of the carrier gas-line radiation which may or may not be desirable.

System optic elements are not only important for their prime functions of transmitting, collecting reflecting and concentrating the radiation, but

they have also an influence on the spectral distribution. In an earlier section of this paper, the difficulty was noted on the absorbtion of UV radiation by optical windows or by the gas in the optical path. The transmission and absorbtion characteristics of each optical element should be part of the selection criteria for that component. The importance of this is indicated in figures 12 through 14 which show the transmission characteristics for several materials.

In general, although not necessarily, the optical system used to accomplish the prime optical functions consists of at least two elements: the collector and the concentrator. The collector is in every case a mirror which may be spherical ellipsoidal, or paraboloidal. The concentrator may be either another mirror or a lens, depending upon the geometrical constraints established by the experimental requirements. The addition of a third element, a secondary collector can be used in some instances to further improve image brightness. The addition of this element is not always compatible with other requirements. Use of a lens as the concentrator generally has the advantage that the light beam is projected completely outside the optical system and offers maximum experimental flexibility. The optical schematic of a radiation lamp developed by Avco RAD shown in figure 15. This system has a paraboloidal primary collector, a spherical secondary collector, and a decentered toroidal biconvex concentrating lens. With a 12 inch lens, a 21 inch working distance is obtained between the lens and the test specimen.

The performance of any arc imaging system can and should be expressed in terms of the radiant flux delivered to the test sample. This performance is dependent on the factors of source brightness, light collection from the source, energy losses in the optical system, and flux losses in the optical system.

1. Source brightness

For opaque sources obeying Lambert's law in systems where the index of refraction of the medium surrounding the source is the same as that surrounding the test region; the brightness at the image cannot exceed the brightness of the source. This is a standard result of optics and is demonstrated in many textbooks. Thus, if the emitted flux into a hemisphere from the surface of a carbon anode is 3 kw/cm^2, the flux received by a sample after imaging cannot exceed this amount and will, in fact, be reduced by any losses.

Care must be exercised in applying this result to plasma radiation sources if they are operated at pressures such that they are optically thin (for most gases this includes operation at pressures up to several tens of atmospheres for dimensions of the order of centimeters). The plasma becomes opaque to wavelengths corresponding to spectral lines at relatively low pressures, but at higher pressures most of the energy is carried by the continuum radiation, and the plasma will not be opaque to this until extremely high pressures are reached). Transparent, volumetric plasma light sources are not Lambert's law sources and their flux can be increased.

The eventual limit for the plasma radiance is that appropriate to a black-body at the plasma temperature. However, it should be noted that the plasma temperature is typically of the order of $15,000^{o}K$, and the corresponding flux is 270kw/cm^2.

2. Light collection

To an approximation of engineering utility, most plasma discharges can be considered as isotropic radiators. Thus, the light-collection efficiency is given by the ratio of the solid angle subtended by the collector(s) to 4π. In all systems, some radiation must be lost; there must be an opening in the system to let the collected beam out, and the electrodes will intercept some radiation. The carbon arc source, in contrast, radiates in general into a hemisphere, with the carbon absorbing the backward radiation.

3. Energy losses

Each optical element in the system absorbs some of the incident radiant energy. These losses can usually be kept small in the visible region of the spectrum, and in the infrared region if the light path does not cross a region which is water-filled. The ultraviolet is more difficult to preserve. In general, reflectances of 0.8 to 0.95 can be obtained for front-surface mirrors and transmissions of the same order for quartz lenses. Figure 12 shows the reflectance of a front-surface aluminum mirror as a function of wavelength, and figures 13, 14 show the transmission of quartz also as a function of wavelength. If the number of optical elements exceeds two or three, these cumulative losses can be quite significant.

4. Flux losses

In general, the size of the radiating volume is not negligible compared to the characteristics dimensions of the optics. Also, very large apertures are required to give good radiation collection, and to illuminate the sample from a large solid angle. Thus, depth of field of the optical system is poor, and the image formed will be a distorted one occupying a larger area than the source. This reduces the flux level at the sample. Also, chromatic

observations and any optical system imperfections will aggravate this situation.

Of the current plasma generators under development or currently being utilized as radiant sources, the following five sources are somewhat representative:

1. A plasma arc source under development which comes closest to combining the features of the vortex-stabilized short arc and the high pressure compact arc is illustrated in figure 16.[30] This unit has been reported as operating at arc chamber pressures of about 20 atmospheres and plasma temperatures of approzimately 7000°K. When this source is operated under properly regulated power and gas flow, it has a cylindrical arc plasma whith a diameter approximately equal to that of the anode exhaust aperture. The cool vortex flow continually replaces the gas surrounding the arc. This constant change of the radiating media accounts for some of the performance differences between the plasma arc source and the high pressure compact arc. The vortex flow also helps to maintain and locate the radiating arc column. The total radiant output of a 10mm x 3mm arc column is reportedly 7.68kw, with an input of 24.8kw when operated with argon. A unit similar to this has recently been developed which operates with input powers up to 150 kw.[31]

This source, as shown in figure 16, has a spherical secondary collector and a paraboloidal primary collector. Thus, the exit beam will be mostly parallel rays with a diameter equal to the paraboloidal diameter. (Finite source size will introduce some convergence and divergence.) No concentrator is specified, although it would be either a second paraboloid or a lens. In the first case, higher flux would be obtained at the expense of experimental flexibility. The light-collection

efficiency appears to be ~0.6, and the transmission efficiency is ~0.7 for the specified elements. A concentrator will reduce this somewhat. The flux delivered to a sample will depend upon the concentrator chosen and will be a function of the desired working distanc; however, it is estimated to be up to 2 kw/cm^2 for sufficiently short working distances.

2. A different approach is utilized in the device shown schematically in figure 17.[29] In most plasma generators the two electrodes are aligned on the axis of the unit. Thus, radiation can emerge only radially. This single-ended arc has a ring-shaped anode surrounding the cathode, which protrudes from the anode plane. The cathode region of the arc at the tip of the cathode is unobstructed over a solid angle of approximately 280 degrees. The reported operating conditions are: Input power 25 kw (units capable of operation at power levels up to 50 kw are under development), 0-300psig chamber pressure, and a 6-mm diameter luminous sphere with a radiant efficiency of 35 percent when operated with argon at 25 kw.

No optics have been specified for this system, however, it should be noted that it differs from the previous system (optically) only by having the anode on the same side as the cathode. Apart from effects this may have on the intrinsic source brightness, there does not appear to be any clear optical advantage or drawback to this arrangement. Roughly, the fraction of the radiation intercepted by the electrodes is the same.

3. A very useful device that has been used as a single unit combined radiative and convective heating source has been referred to as a modified tandem Gerdien,arc.[22] In this source, the test gas, air or other gases of interest, is heated in an arc column which is partially constricted by vortex flow and by mechanical orifices, figure 18. The test model is

positioned in close proximity of the arc column which provides the radiant energy. Previous column temperature measurements made on an arc of this type indicated peak temperatures between 16,200 - 18,000 $^{\circ}K$.[32]

The temperature profile of the column has not been reported. Slightly less than 800 BTU/ft^2-sec radiative heat transfer from air was measured by a radiation cavity gage at a distance of approximately 1 cm from the column boundary, with an input of 250 KW and one atmosphere chamber pressure. A unit is currently under development will allow operation at pressures up to 5 atmospheres and will permit adjustment of model position to vary the radiant energy transfer.

This source does not appear to be well suited for imaging without further arc modification. A particular value of this source is that the spectral distribution and flux can be made to match the gas and flight conditions of interest. It does, however, limit model size and is somewhat nonuniform. Most of the models tested have been char formers which has tended to nullify the nonuniformity effects.

4. The fourth plasma arc generator source of intrest is shown in figure 10. This device has produced a radiation flux of over 5 kw on a target area of 10 cm^2 when operated at about 100 kw, 25 atmospheres chamber pressure with argon as the radiating media. A major difference between this source and the first source discussed is the inclosure of both of the collection reflectors within the arc chamber envelope. The optics of this source are shown in figure 15. The flexibility of this type of source is shown in figures 11 and 19 where 4 units have been installed in conjunction with a several megawatt convective arc heater (The AVCO RAD ROVERS facility). The moderately long, 21 inches, working distance between the target and the condensing lens permits the multiple mounting

arrangement with only a moderate cosine loss (a function of the source angle with normal incidence at the target). The gimballed source mounting and adjustable lens positioning system permitts near optimum radiation testing of models from 1½ (fluxes of over 1 kw/cm^2) to approximately 4 inches in diameter.

The potential flux uniformity of a source of this type is reflected in the data shown in figure 20. This data was taken with a single source operating at an input power of 80 kw. The flux was measured with a blackened water cooled copper calorimeter. No attempt was made to correct the data for the calorimeter emissivity. (Subsequent measurements taken with the condensing lens have demonstrated fluxes of over 500 watts/cm^2 over similar areas.) By replacing the lens with a second paraboloidal mirror, thus appreciably shortening the working distance, a flux of several kw/cm^2 may be achieved.

5. One other type of plasma arc radiation source is starting to show promise but lacks definitive data at the present time. This source is similar to the first type discussed but features a significantly longer arc column. This type of device is being studied by several laboratories[33]; one has been operated at AVCO RAD at 300 kw and soon will be run at power levels over a megawatt.

SUMMARY

An attempt has been made to define the requirements for simulation of radiant heating attendant to atmospheric entry. At the higher super-orbital velocities, uncertainty factors of over 2 exist in the radiative heat flux estimates. In particular there is a great uncertainty in the levels of UV radiation and its effect on the vehicle. Due to a significant lack of data, it is dificult to relate the environment

parameters to simulation requirements. The most promising source to meet the radiation heating simulation requirements is the plasma arc generator. This type of source coupled with an appropriate convective heating system will provide the extension of entry simulation capability required to determine the effects of radiatiative and combined radiative-convective heating on entry vehicles and materials.

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TABLE I
SOURCE EVALUATION SUMMARY

Source	Flux-Max	Size Limit (inches)	Uniformity	Time Stability	Spectral Match With Air	Compatability with Convective Source	Remarks
Sun	3660BTU/ft^2sec	~ 1	Poor	Good	Fair	Fair	Cost moderate to high. Not always available.
Carbon Arc	915BTU/ft^2sec (3660 under pressure)	1/3	Poor	Poor	Fair	Fair to good	Cost low to moderate. Short-time operation.
Carbon Vapor Lamp	Unknown	~ ½	Poor	Medium	Poor to fair	Fair to good	Not in hardware stage.
Electrical Resistors	300	Dependent only on size of power supply	Excellent	Excellent	Poor to fair	Fair to good	Low Cost-Great flexibility in size and shape.
High Pressure Compact Arcs	100-500	1-½	Poor	Good	Poor	Fair to good	Moderate to high cost. Continuous operation possible
Plasma Generator (Plasmadyne Type)	Good*	*	Poor to fair	Good	Poor to fair	Good*	Moderate to high cost.Continuous operation
Plasma Generator (Vitro Type)	Good*	*	Poor to fair	Good	Poor to fair	Good*	Moderate to high cost.Continuous operation
Plasma Generator (G.E. Tandem Gerdien)	1000BTU/ft^2sec	3/4	Poor to fair	Good	Good	Good but limited Model size	Moderate to high cost.Continuous operation
Plasma Generator (Avco RAD Type)	1000-2000BTU/ft^2sec	1½ at maximum flux. Larger size with reduced flux	Poor to fair	Good	Poor to fair	Good	Moderate to high cost.Continuous operation
Electron Beam	100 BTU/ft^2sec	2	Good	Good	Poor to fair	Poor	High Cost
Laser	100,000BTU/ft^2sec for a 3/4-inch Model	3/4	Poor to fair	None	None	Good	Moderate to high cost.Test time 2×10^{-3}sec.

*Devices have not as yet been coupled with Optimum Optics, therefore performance not fully established.

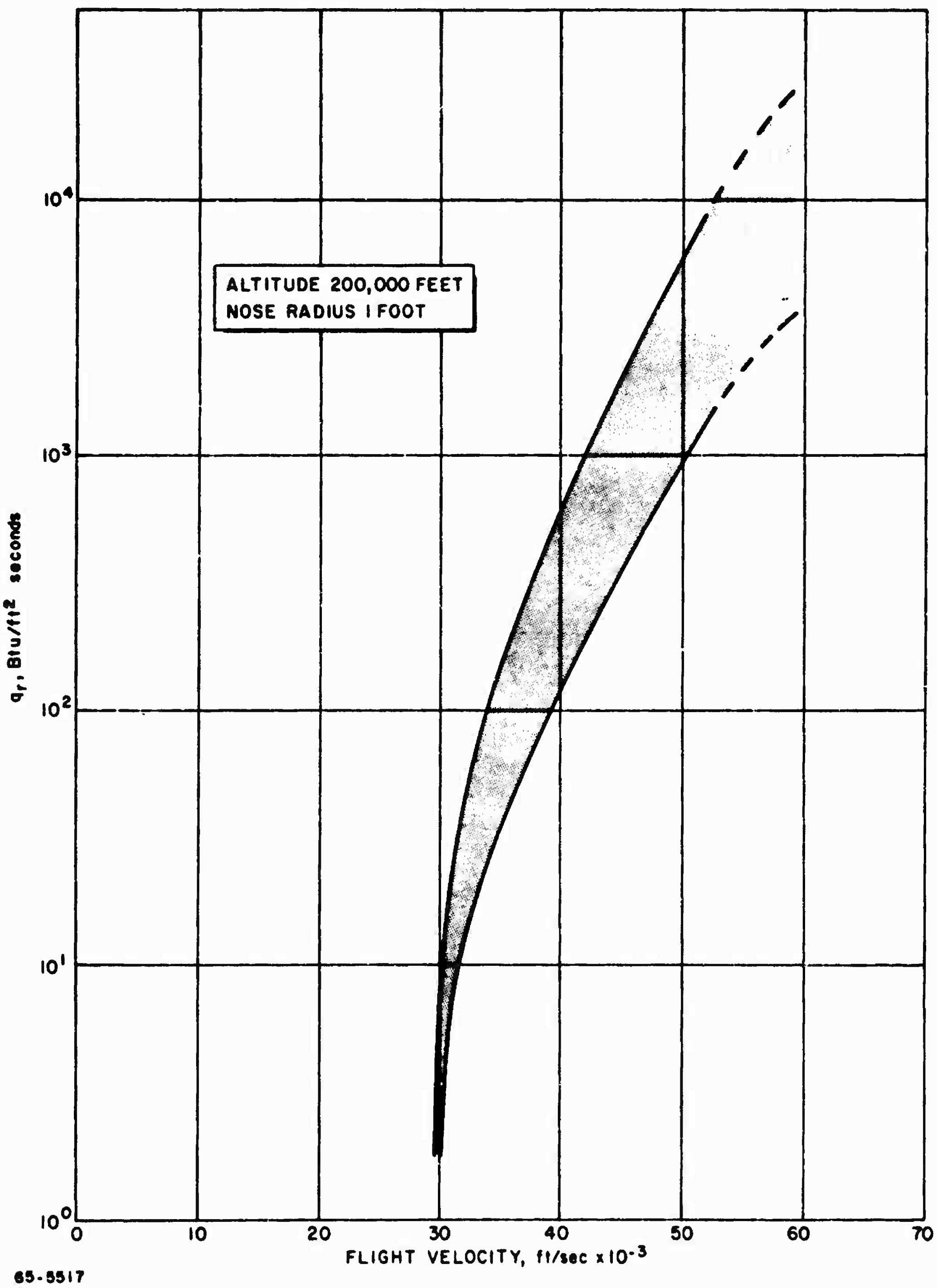
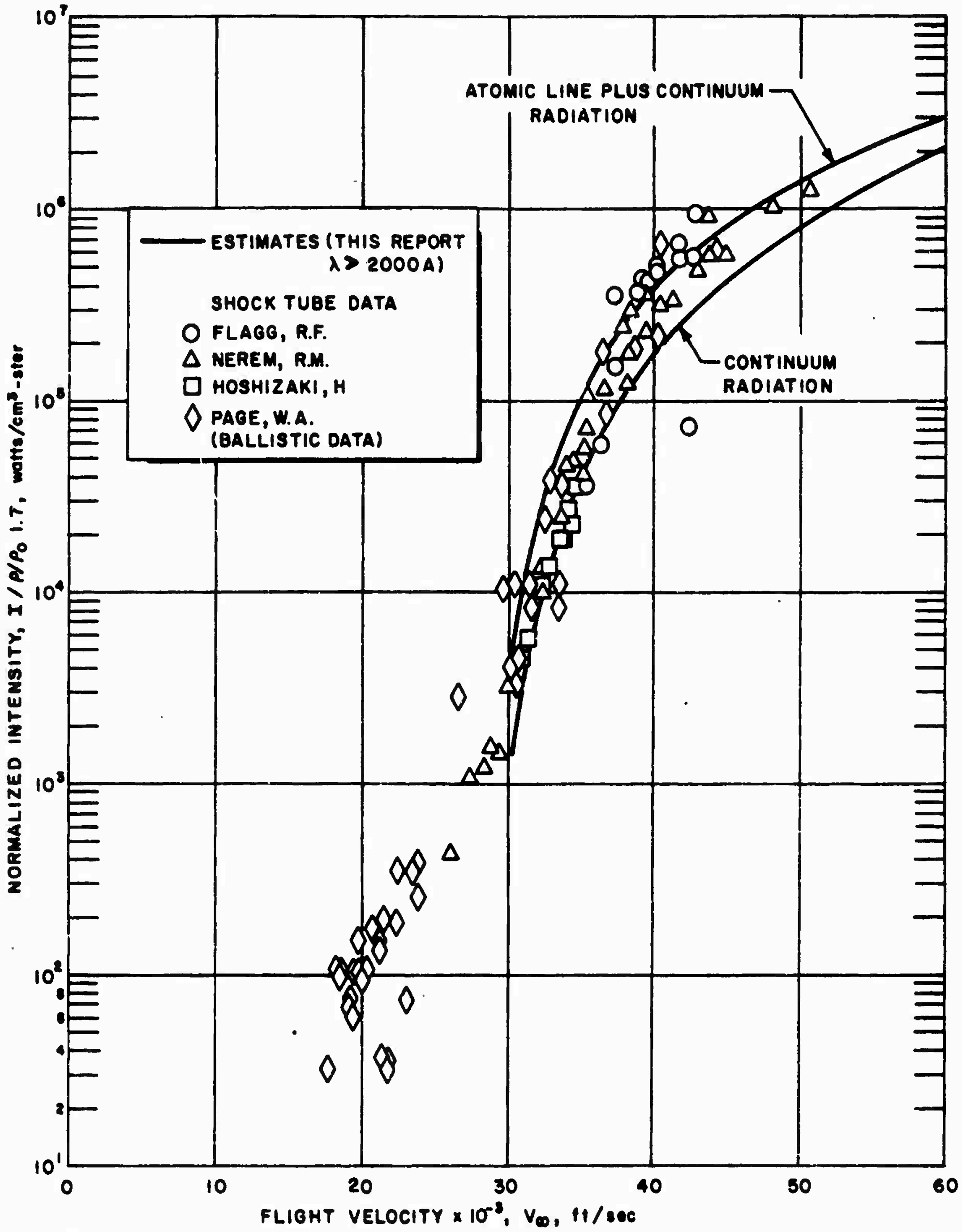
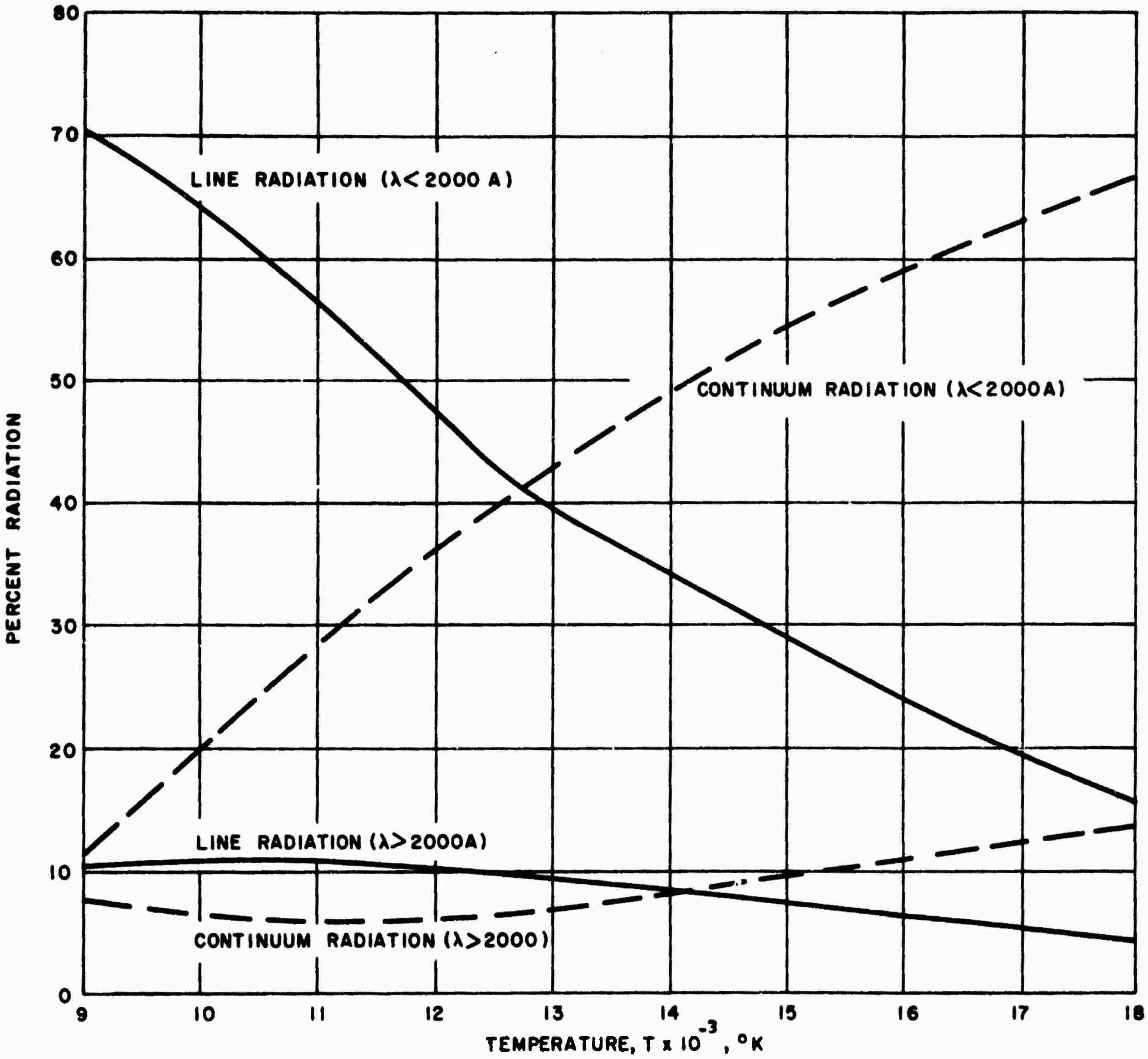


Figure 1 EQUILIBRIUM RADIATION DATA AND UNCERTAINTY BAND



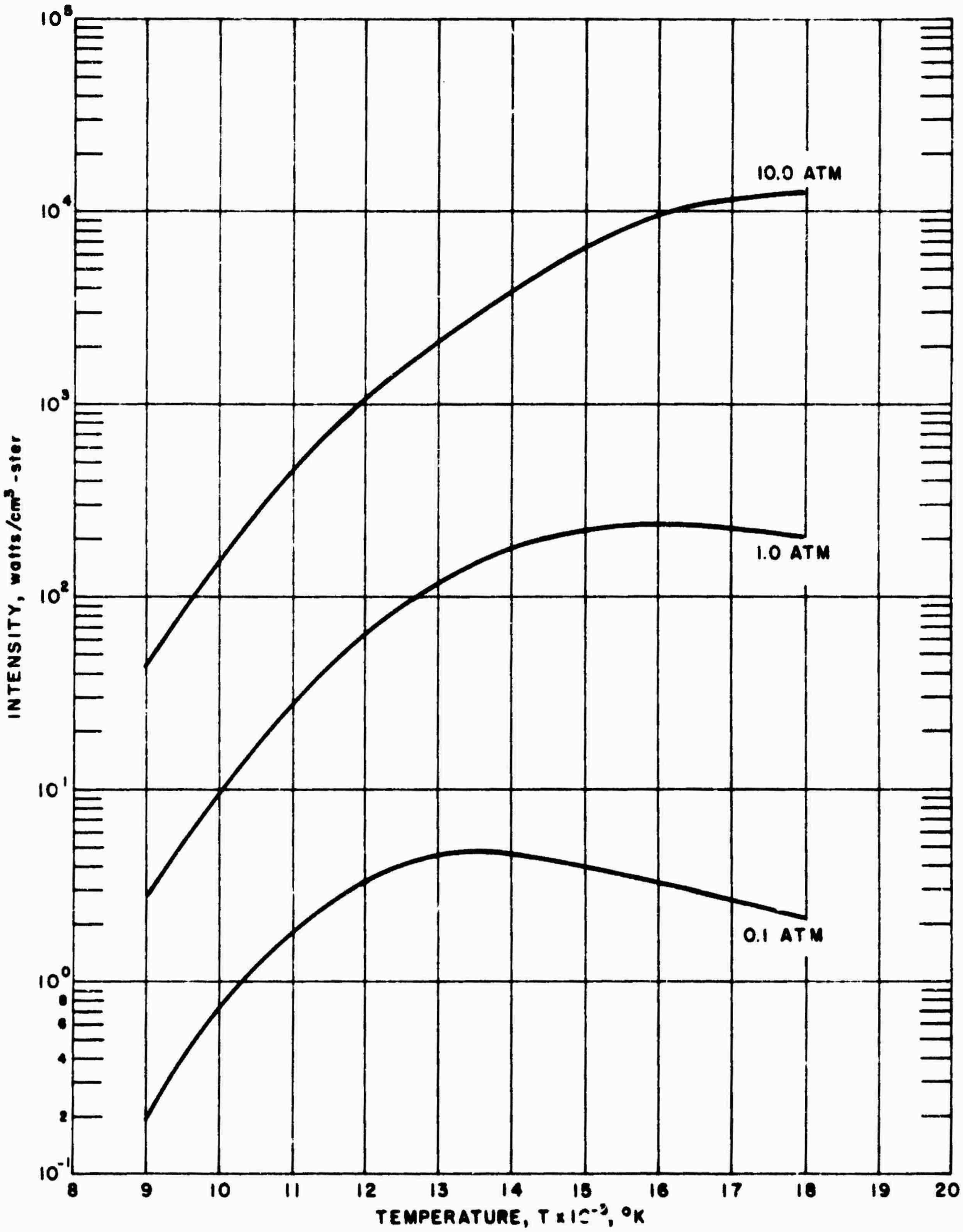
68-9693

Figure 2 NORMALIZED INTENSITY VERSUS FLIGHT VELOCITY; COMPARISON OF SHOCK-TUBE, BALLISTIC RANGE, AND ARC COLUMN RADIATION DATA



65-9682

Figure 3 PERCENT CONTRIBUTION OF ATOMIC LINE AND CONTINUUM RADIATION AS A FUNCTION OF TEMPERATURE FOR NITROGEN



65-9679

Figure 4 ATOMIC LINE PLUS CONTINUUM RADIATION FOR AIR VERSUS TEMPERATURE AT VARIOUS PRESSURE LEVELS (λ > 2000 Å)

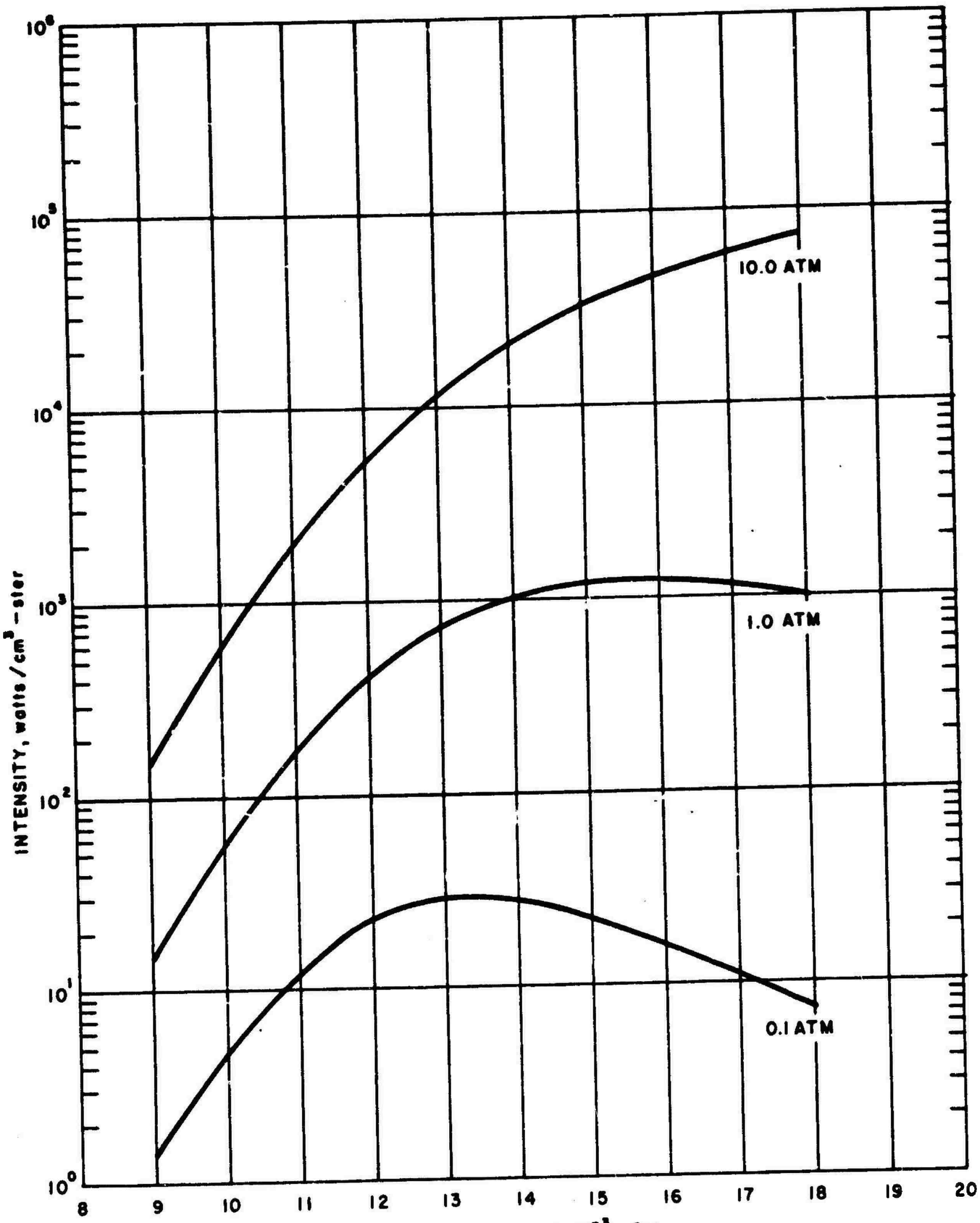


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Figure 5 ATOMIC LINE PLUS CONTINUUM RADIATION FOR AIR VERSUS TEMPERATURE AT VARIOUS PRESSURE LEVELS ($\lambda > 0.0$ Å)

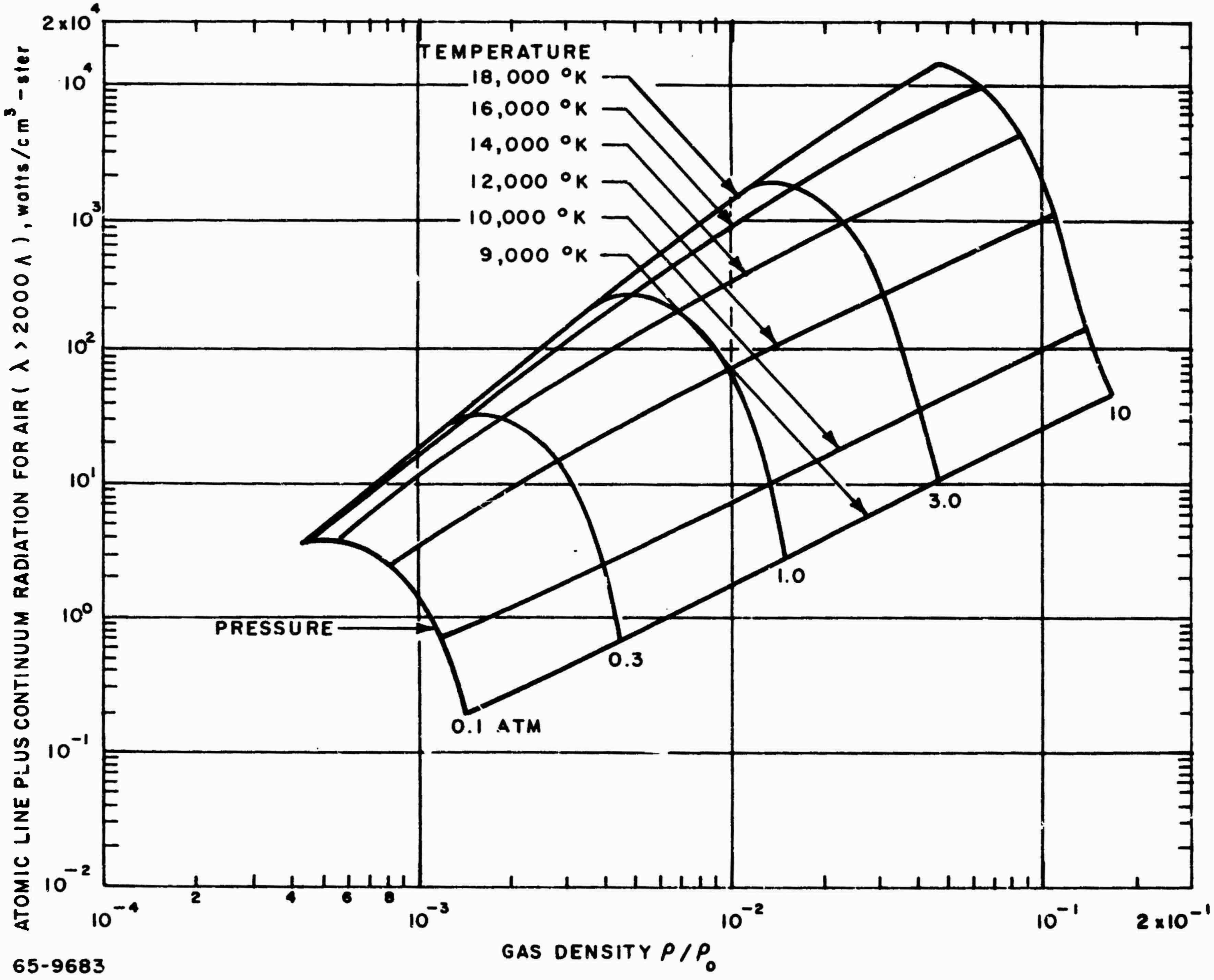


Figure 6 ATOMIC LINE PLUS CONTINUUM INTENSITY FOR AIR AS A FUNCTION OF GAS DENSITY RATIO AT CONSTANT TEMPERATURES AND PRESSURES ($\lambda > 2000$ Å)

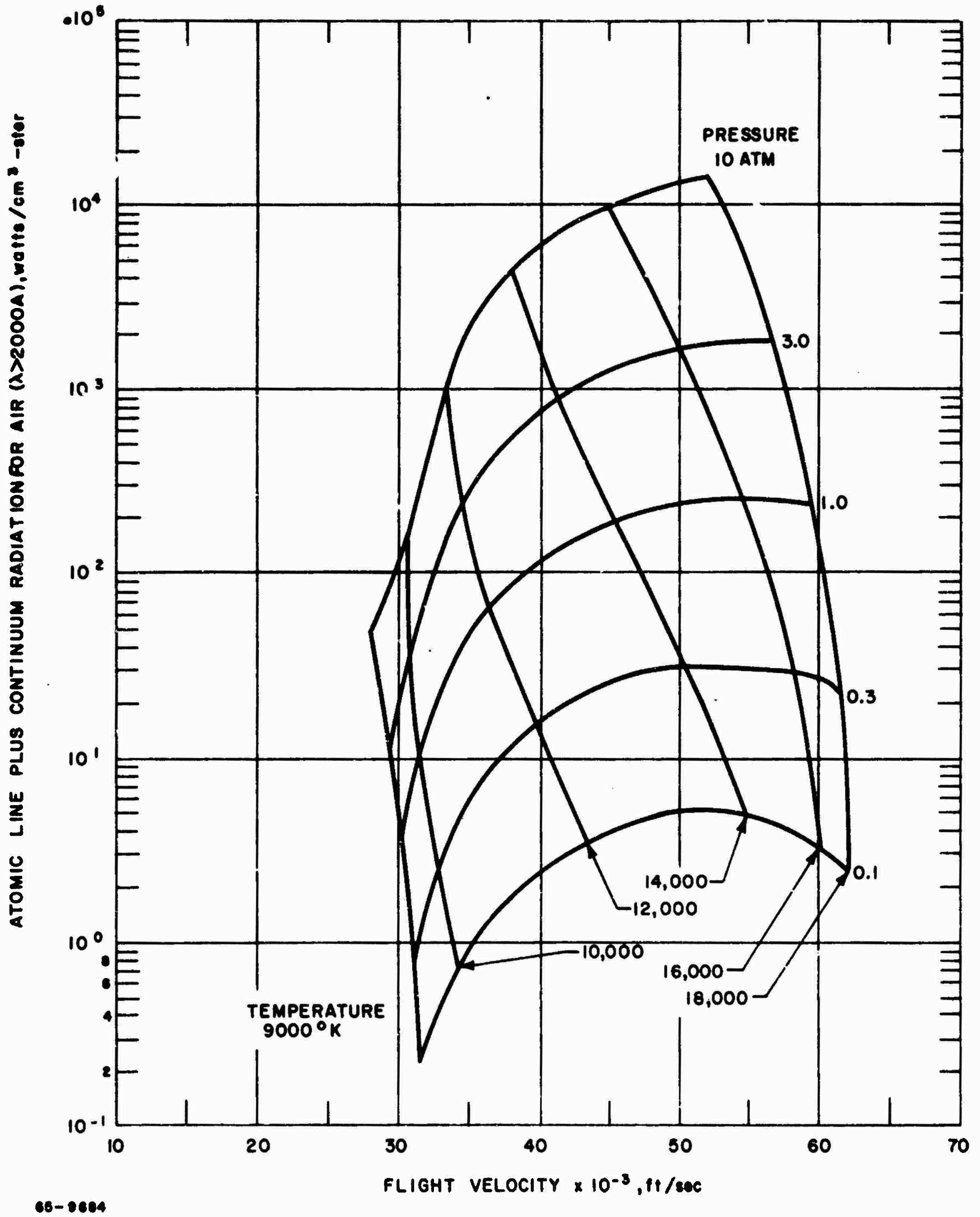


Figure 7 CONTINUUM PLUS ATOMIC-LINE RADIATION FOR AIR AS A FUNCTION OF CONSTANT PRESSURES AND TEMPERATURES VERSUS FLIGHT VELOCITY

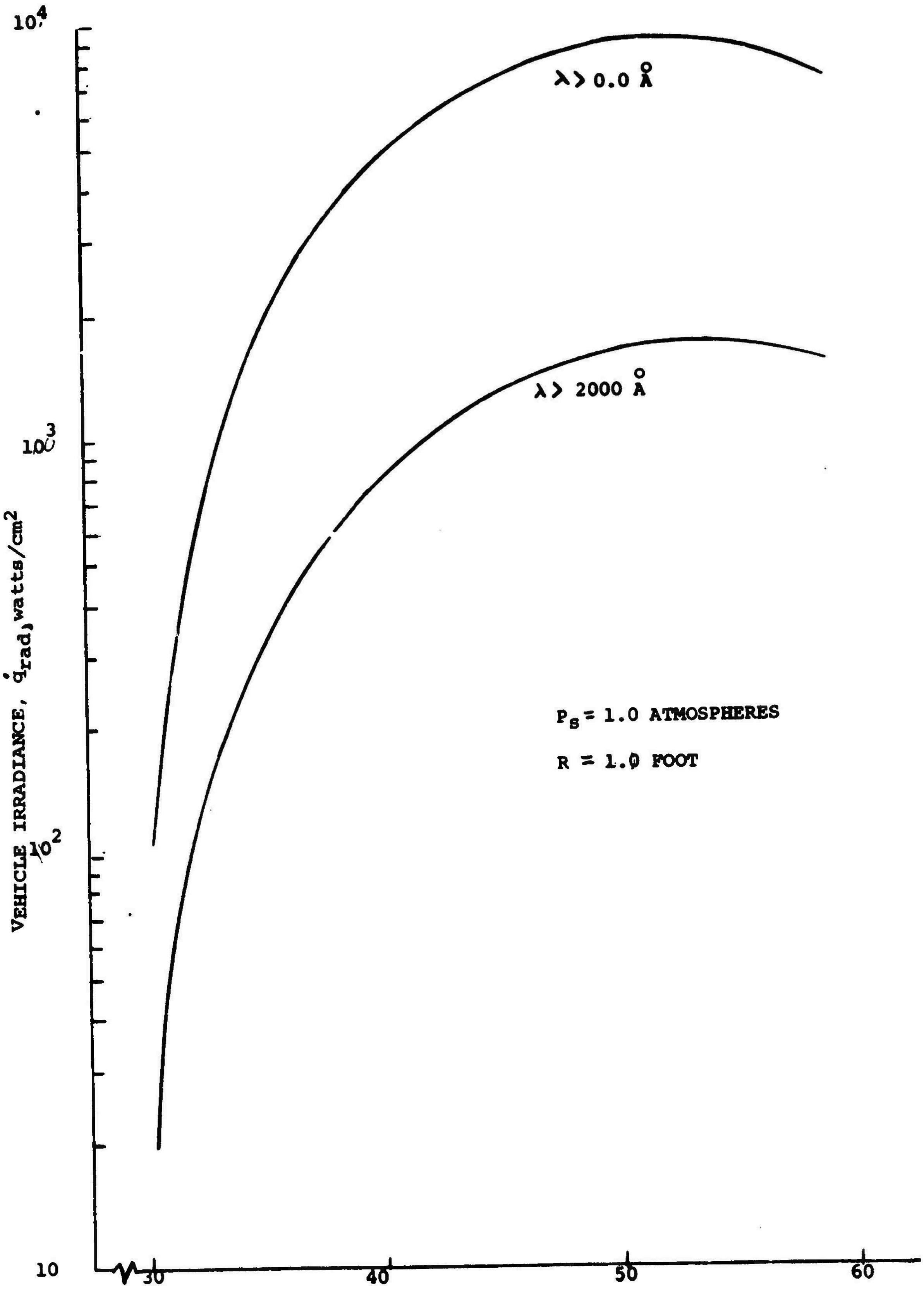


Figure 8 SIMULATED FLIGHT VELOCITY, $V_\infty \times 10^{-3}$ FT/SEC

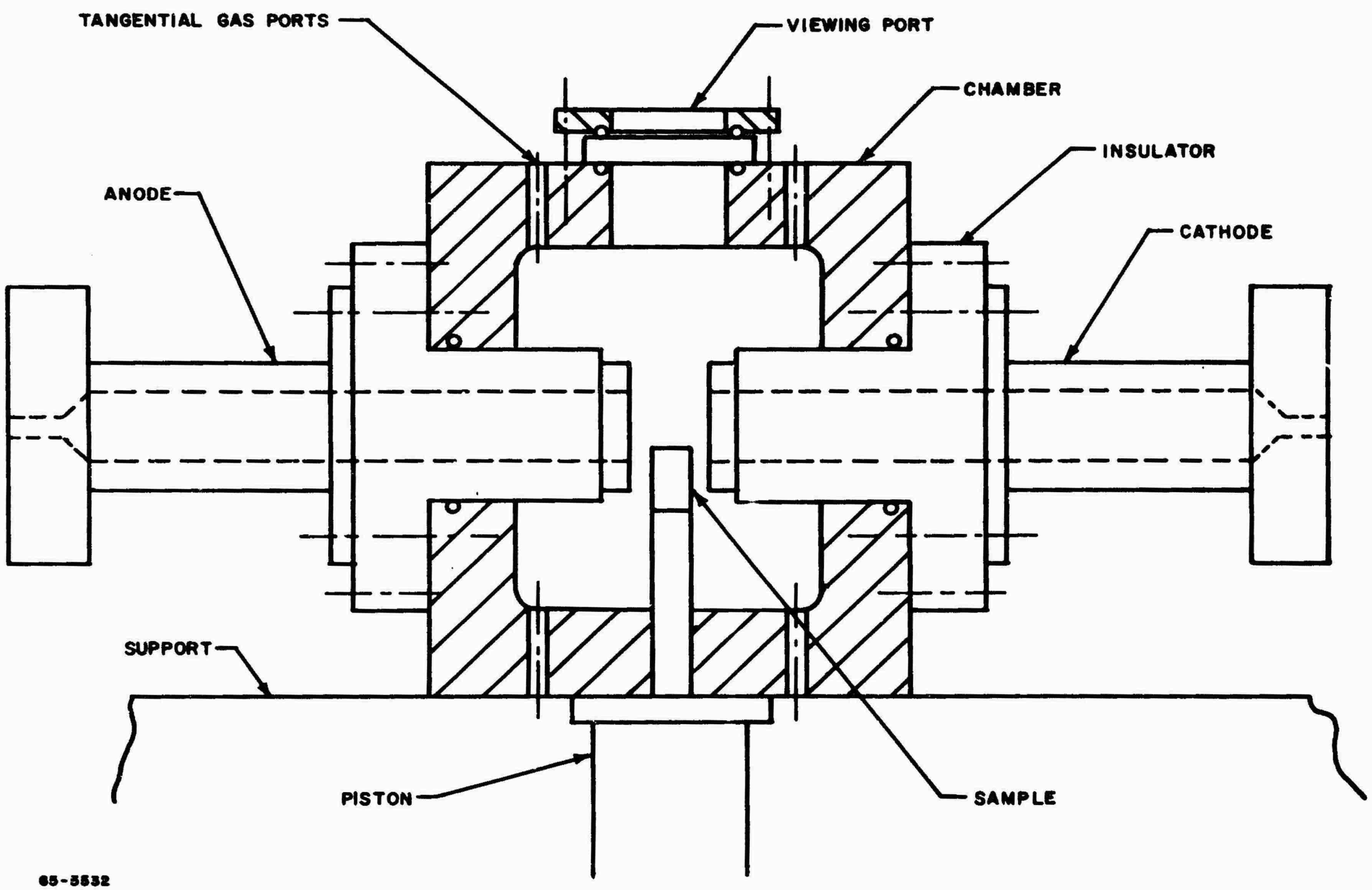
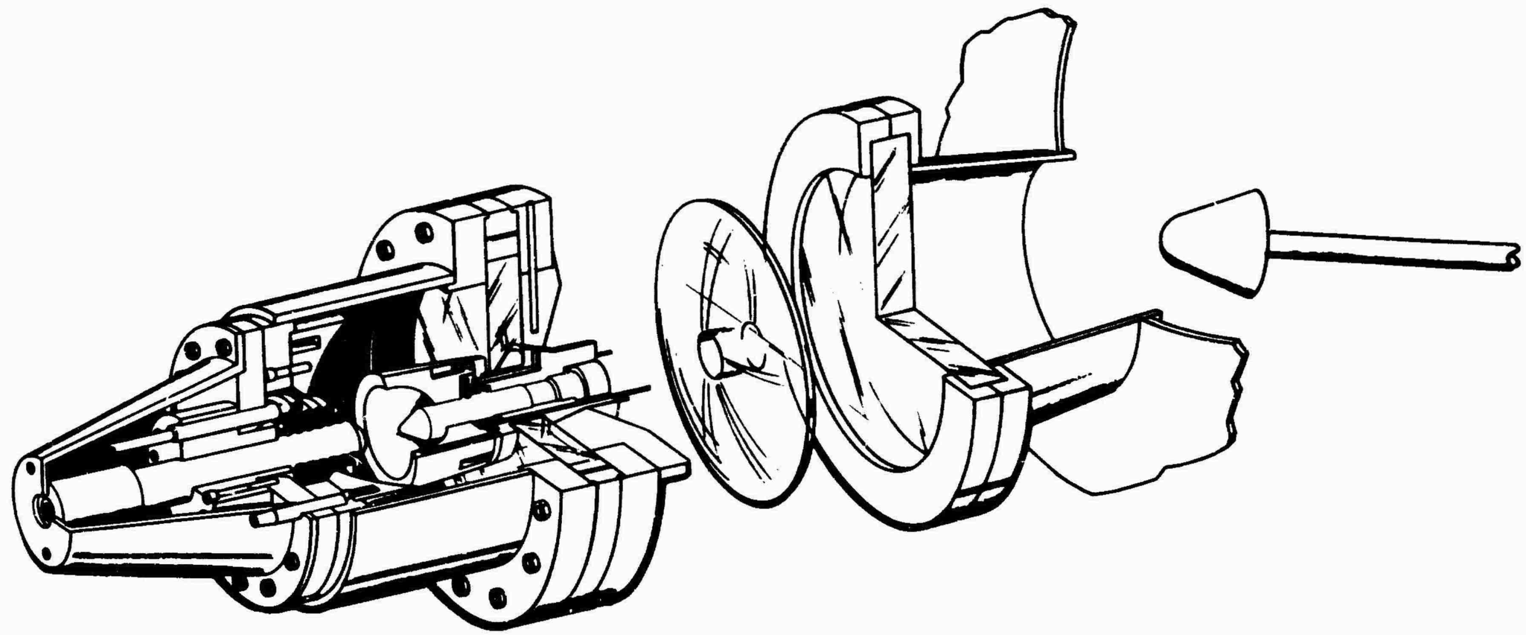
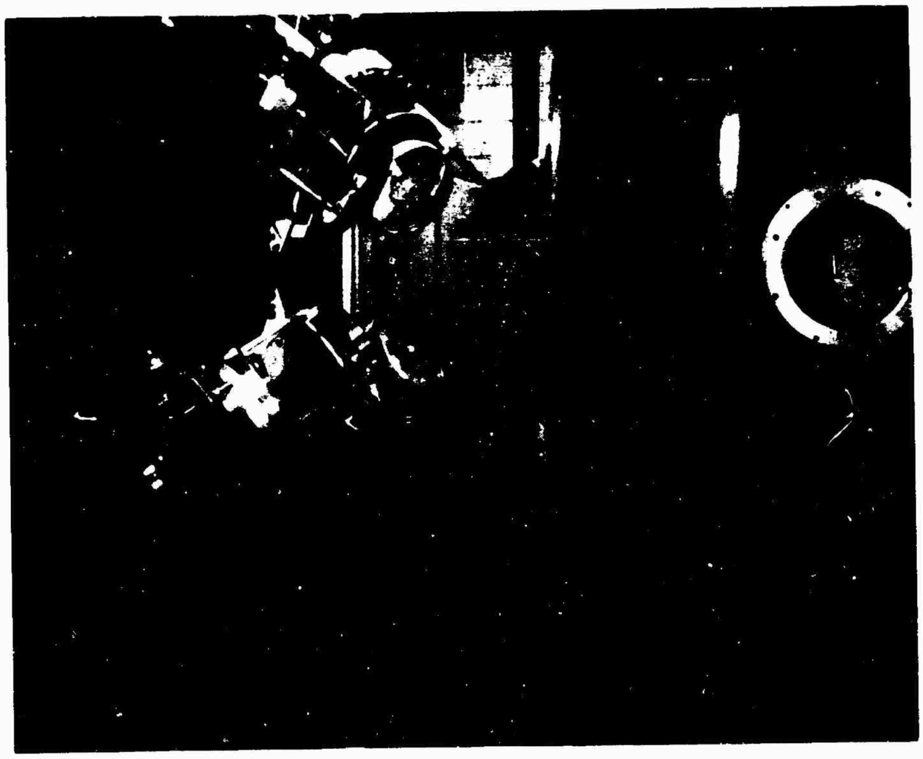


Figure 9 CROSS SECTION OF CONSTRICTED ARC

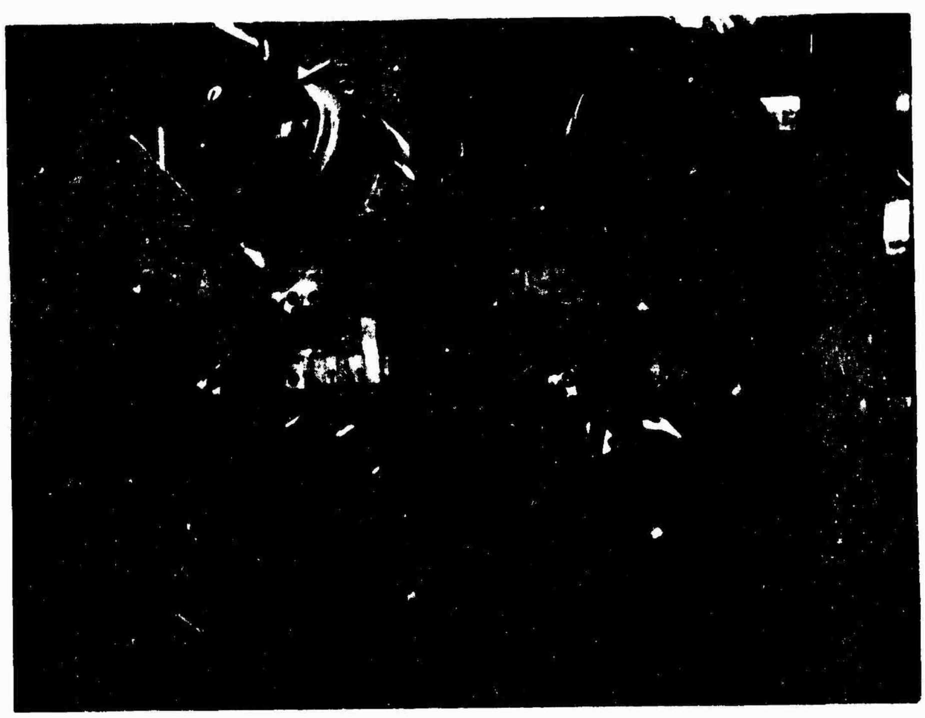


E8-5533

Figure 10 PLASMA GENERATOR RADIATION SOURCE



FRONT VIEW



BACK VIEW

Figure 11 MULTIPLE MOUNT OF PLASMA GENERATOR RADIATION SOURCES WITH ASSOCIATED OPTICS, AVCO RAD ROVERS FACILITY

DATA TAKEN FROM
LIBBY-OWENS-FORD GLASS COMPANY

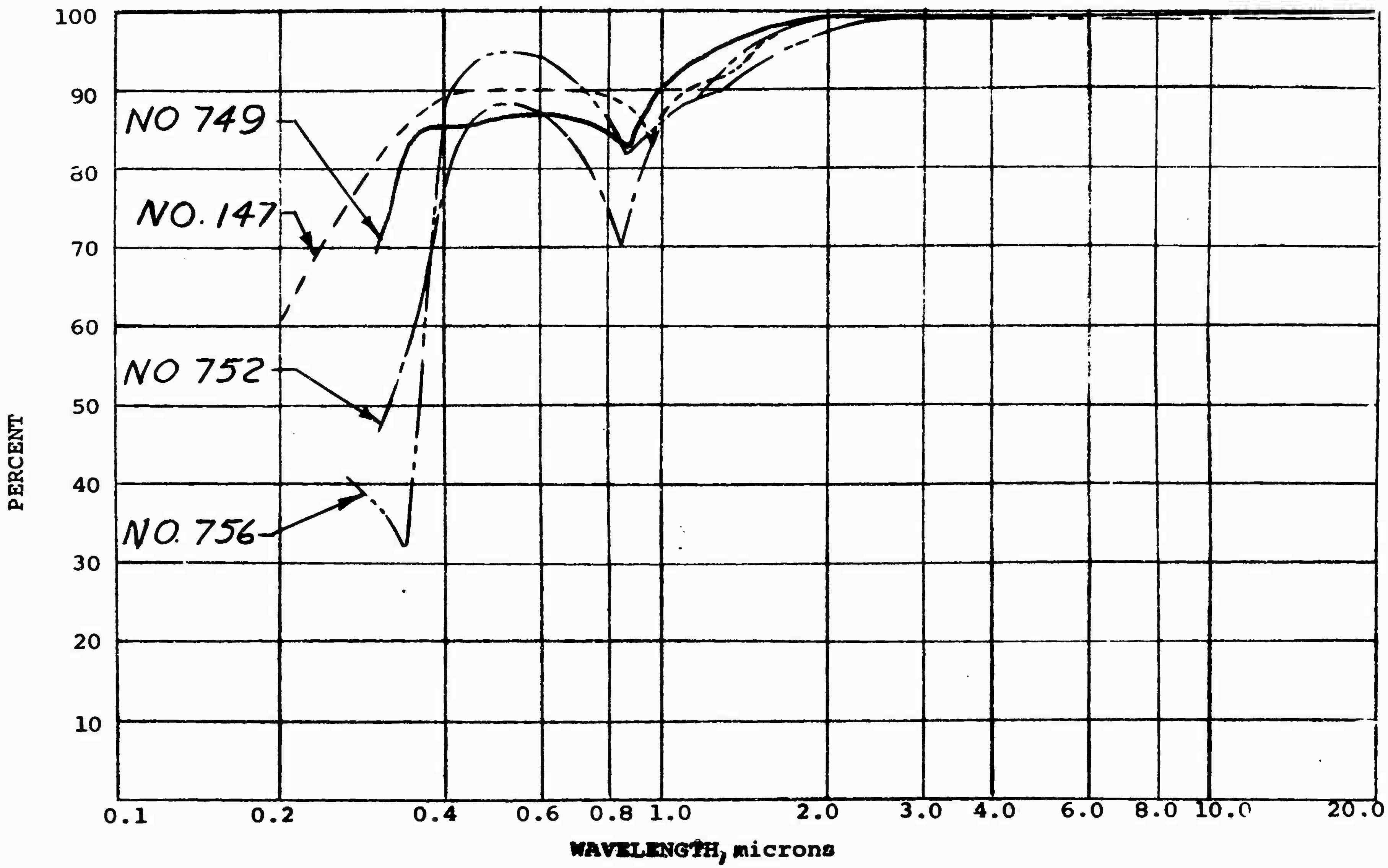
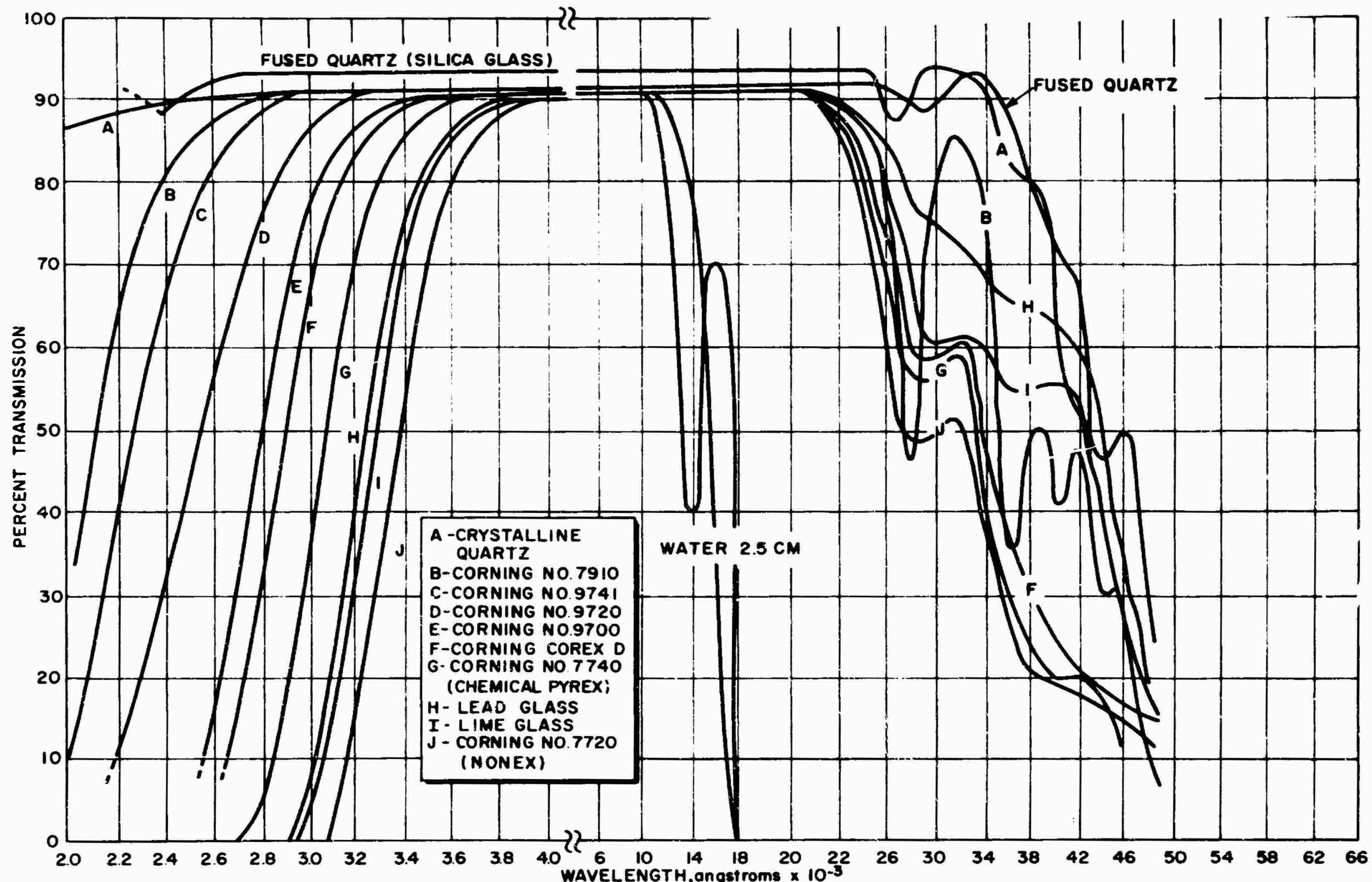


Figure 12 PERCENTAGE REFLECTENCE OF AN ALUMINUM MIRROR

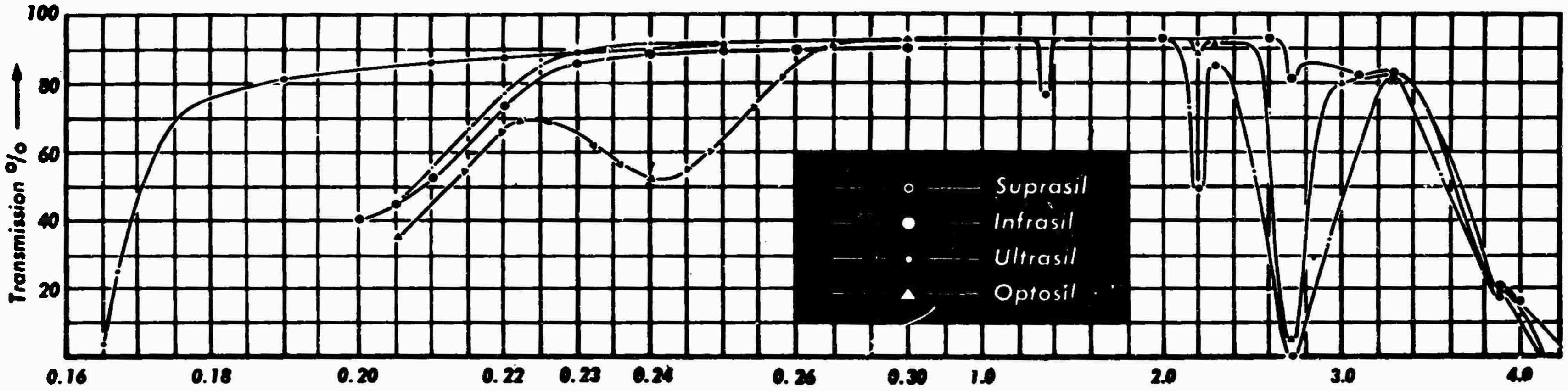


65-5543

Figure 13 TRANSMISSION CHARACTERISTICS OF QUARTZ, VARIOUS GLASSES AND WATER

DATA TAKEN FROM ENGELHARD INDUSTRIES, INC - E1-1056-2

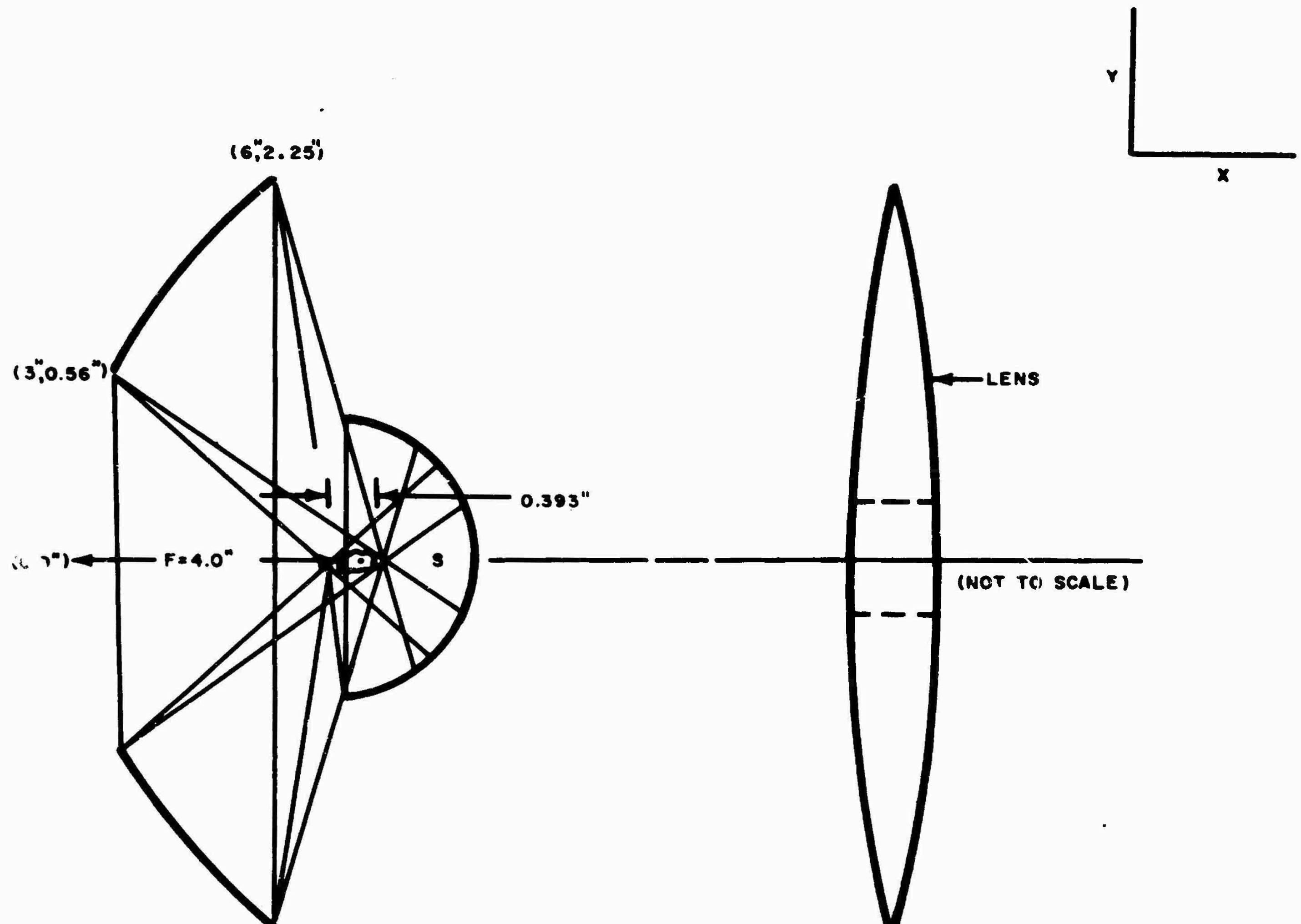
PERCENT TRANSMISSION OF ENTERING ENERGY



MEASUREMENTS MADE THROUGH A TEN MM THICKNESS IN EACH INSTANCE · WAVELENGTH IN MICRONS

*Optosil, Homosil and Commercial Grades have same basic transmissions.

Figure 14 TRANSMISSION CHARACTERISTICS OF FUSED QUARTZ



65-5540

Figure 15 PARABOLOID-SPHERICAL REFLECTOR AND CONCENTRATING LENS OF AVCO RAD SOURCE

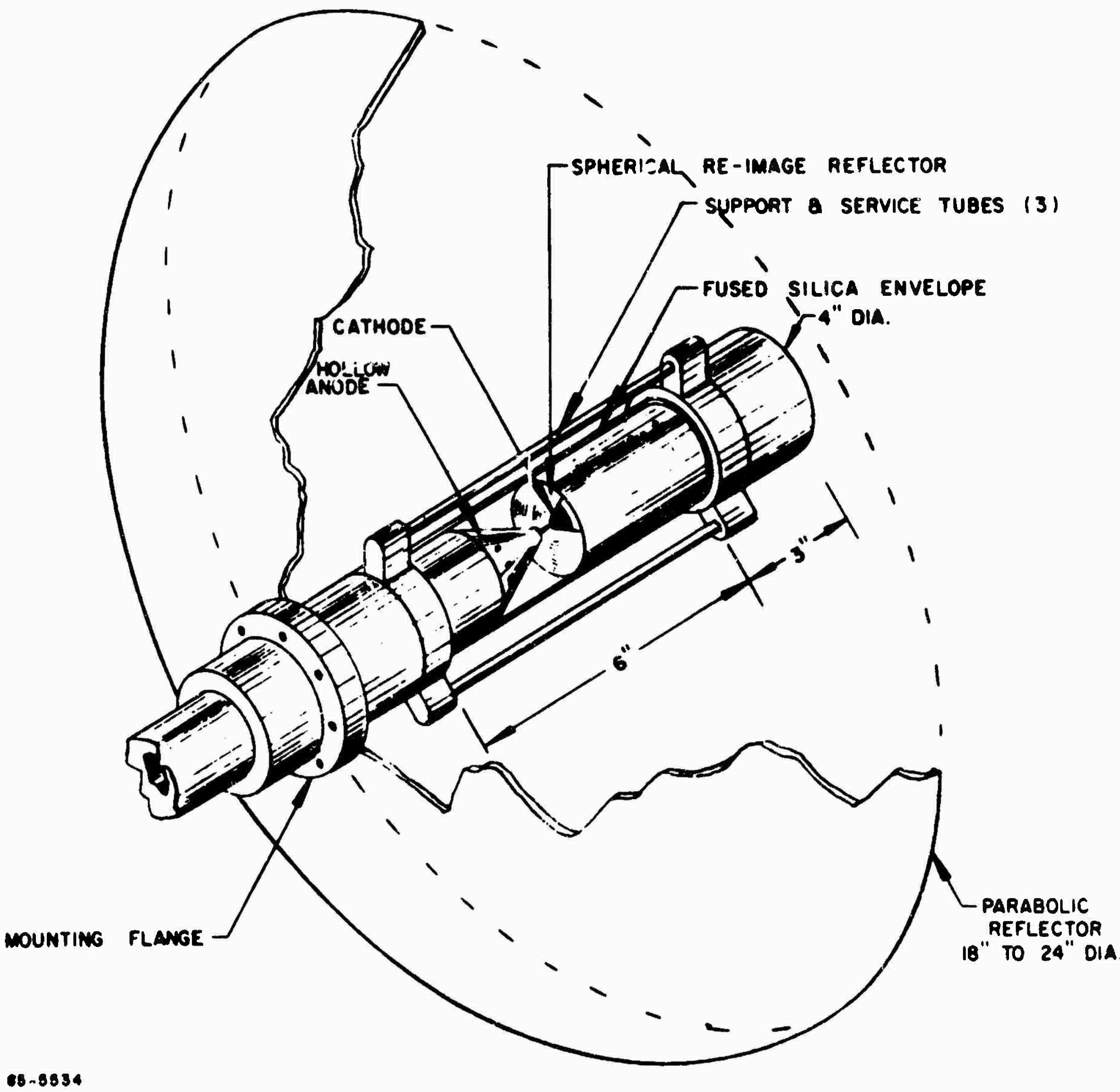
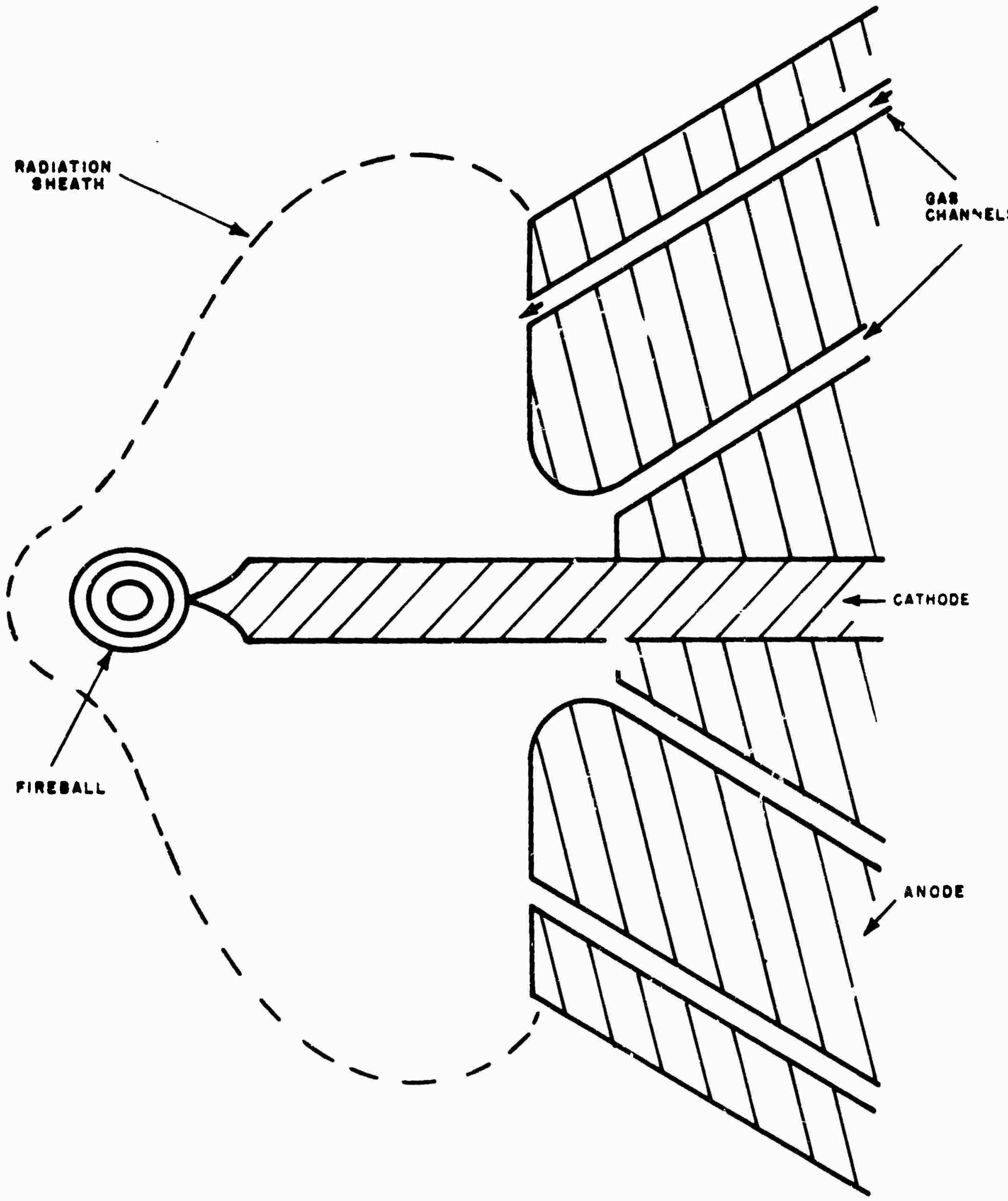


Figure 16 VORTEX STABILIZED RADIATION SOURCE



65-5535

Figure 17 SKETCH OF VITRO RADIATION ARC

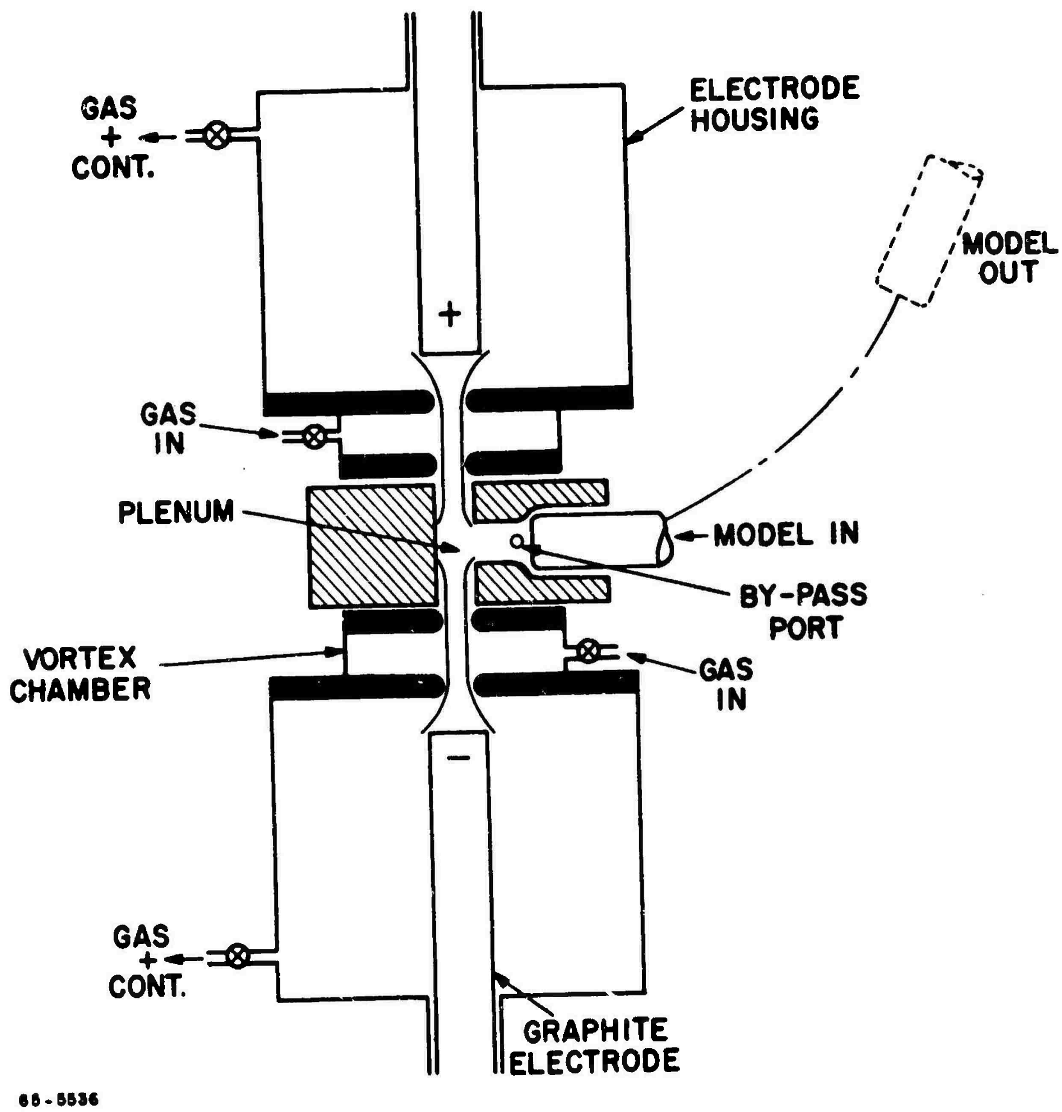
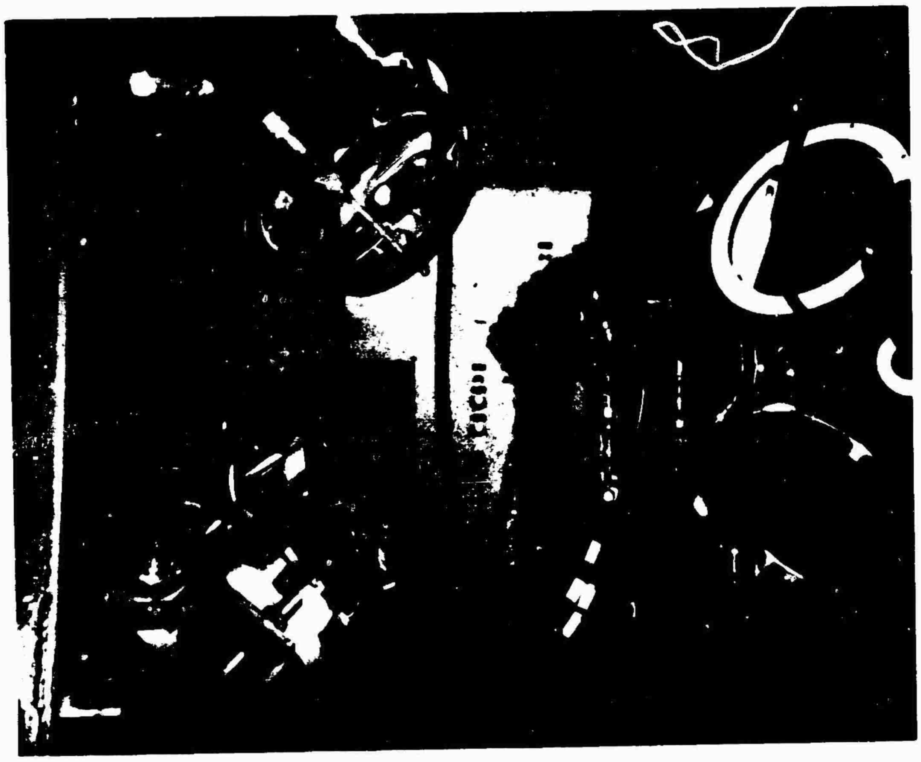


Figure 18 SCHEMATIC OF MODIFIED TANDEM GERDIEN RADIATIVE AND CONVECTIVE HEATING ARC SOURCE



RADIATIVE AND CONVECTIVE HEATING SOURCES

VACUUM CHAMBER

Figure 19 AVCO RAD ROVERS FACILITY

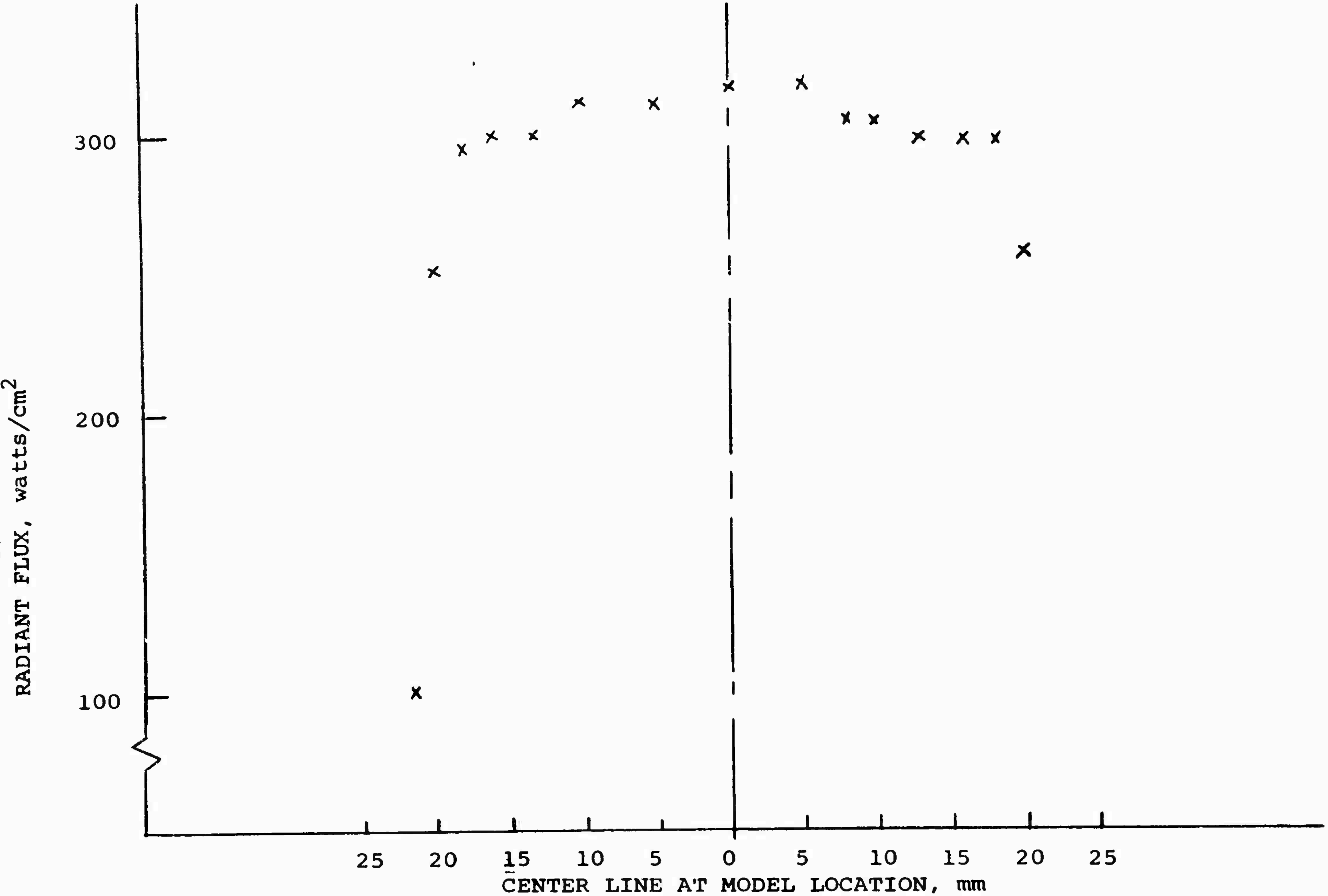


Figure 20 **RADIANT FLUX DISTRIBUTION ON TARGET AREA FROM A SINGLE SOURCE**